CERAMIC EXTERNAL PRESSURE HOUSINGS FOR DEEP SEA VEHICLES

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ABSTRACT--Only glasses, ceramic and carbon fiber reinforced plastic can provide the necessary weight to strength ratio to make the external pressure housings for undersea vehicles positively buoyant at the abyssal design depth. This group of materials poses unique challenges to the designer and fabricator of pressure housings. This paper summarizes the findings of the R & D program aimed at developing the technology for the design, fabrication, and testing of ceramic housings culminating in the application of ceramic housings to the WHOI ROV/AUV diving system with 36,000 ft (11,000 m) capability (Figure 1).

INTRODUCTION

The concept of external pressure housings was introduced in 1961 by Dr. J.D. Stachiw at the Ordnance Research Laboratory at Pennsylvania State University. The materials selected for construction of housings were 94 % Al_2O_3 and Pyroceram Code 9606© ceramics, readily available from COORS Ceramic Co. and Corning Glass Works, respectively. Their physical properties were significantly superior to available metallic alloys (Figure 1)

Glass was not seriously considered because of its low tensile strength, providing low resistance to crack initiation and propagation on the bearing surfaces of housings. Casting of Pyroceram 9606© cylinders requires special equipment as it begins its fabrication cycle as molten glass. The only reason Pyroceram 9606© was chosen for the ceramic housing development program at ORL was because equipment for spin casting of 12 in cylinders and ogives was available at that time at Corning Glass Works and was funded by a major U.S. Air Force rocket production program for the fabrication of rocket housings.

ORL Ceramic Housing Program

The ORL ceramic housing program concentrated on cylinders 12.75 in diameter suitable for construction of housings for oceanographic instrumentation with 20,000 feet depth capability. A number of 8 and 12 in diameter rib stiffened cylinders were fabricated from 94% Al_2O_3 and Pyroceram 9606© glass ceramic and tested under external pressure (Figure 2). The program was, after fabrication and pressure testing of an 82 in x 12.75 in torpedo shaped Pyroceram 9606©housing, terminated in 1966 due to lack of funding.

The **findings** of the program (References 1, 2, and 3) were very encouraging for the potential application of ceramics to housings for oceanographic or military applications at depths to 20,000 feet.

1. Analytical expressions developed for the distribution of stresses and elastic stability of metallic rib stiffened cylinders apply equally well to ceramic cylinders.

2. Rib stiffened ceramic cylinders did not fail under a **single pressurization** test so long as the principal compressive stresses were less than 300,000 psi, principal tensile stresses were less than 20,000 psi, compressive axial bearing stresses at the ends of the cylinders were less than 100,000 psi, and the cylinder was sufficiently stable to prevent failure in the local or general elastic instability modes.

3. Cyclical pressurization fatigue life of rib stiffened cylinders appears to be a function of both the maximum principal stresses, as well as of bearing stress at the joints. When the average **compressive axial bearing stress** was less than 30,000 psi, the **maximum principal compressive hoop stress** less than 200,000 psi, and **shear stress** less than 10,000 psi, the ceramic capsules demonstrated a cyclical life of $\geq$ 1000 cycles when resting on a bare flat metallic joint ring.

4. Capsules with standard commercial flatness finishes on the joint bearing surface perform best when placed on a 0.020 in thick neoprene gasket reinforced internally with nylon cloth. A flat metallic bearing surface without gasket is less desirable, but acceptable.

5. Metallic joints were developed that not only seal joints between two ceramic capsule components, but also mechanically tie the two capsule sections together into a single structural unit. Prime requirements of such a joint are small mass for low rigidity, and flat bearing surface for the ceramic capsule and stiffeners.

7. The resistance to dynamic pressure loading of ceramic cylinders increases with depth.

NOSC Ceramic Housing Program

With the renewed interest in deep diving ROV's and AUV's, the Naval Ocean Systems Center in San Diego, CA in 1984 initiated an in-house research program with Dr. Stachiw as the manager, on application of ceramics to construction of pressure

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housings for deep diving ROV's and AUV's. The **objectives** of this program were fourfold.

1. **Selection of most cost effective ceramics**, and housing configuration of pressure housing design.
2. **Selection of the most economical and reliable design** for joining of ceramic housings.
3. **Establishment of cyclic fatigue limits** for the ceramic compositions considered for housing fabrication.
4. **Design of penetrations** in ceramic hemispheres.

Objectives 1, 2, and 3 were met by fabrication and pressure testing of 6 in OD x 0.205 in T x 9.0 in L, 12 in OD x 0.413 in T x 18 in L, and 20 in OD x 0.685 T x 30 in L ceramic cylinders designed on the basis of 135,000 psi maximum nominal hoop compressive stress at 9,000 psi external pressure.

Ceramics used for their fabrication were 99.5% Al_2O_3, 96 % Al_2O_3, 94 % Al_2O_3, Zirconia Toughened Al_2O_3, SiC Particulate Reinforced Al_2O_3, Si_3N_4 and BeO. Pyroceram 9606© was not included in this program as Pyroceram 9606© was not any more available from Corning Glass in cylindrical or spherical custom castings at affordable cost since the termination of the Air Force ceramic rocket housing program utilizing rotomolding equipment at Corning Glass.

Of the ceramics used in the fabrication of housings, only Si_3N_4 housings were found to provide the lowest weight to displacement and longest cyclic fatigue life. Alas, the cost of their fabrication and requirements for special equipment in their fabrication precludes the use of this ceramic for inexpensive fabrication of large housings. The same could be said for BeO ceramic.

Thus the real evaluation of structural performance narrowed down to alumina ceramic compositions. Of these only 96 % Al_2O_3 and SiC Particulate reinforced Al_2O_3 were found to be the most cost effective ceramic compositions for large cylinders and hemispheres; i.e., they provided the longest cyclic fatigue life in large pressure housings at the lowest cost.

The objective No. 4 was met by fabrication and testing of 12 in OD hemispheres with penetrations. All were true hemispheres with edge bearing surface width only 50 % of the cylinder thickness. As a result, the bearing stress on their edge at 9000 psi pressure was 130,000 psi, while the bearing stress on the cylinder ends was only 65,000 psi. Because of the high axial bearing stress, cracks appeared in the edge of the spheres after only 100 pressure cycles.

Different approaches were used to reduce the stress around the penetrations. In the case of the hemisphere having one or more holes, a 100 % increase in thickness lowered the compressive stress at the penetration below 200,000 psi. In such hemispheres equipped with titanium end rings when pressure cycled the cracks appeared first at the equatorial bearing surface, and not at the penetrations.

To postpone the appearance of cracks on the edge of the hemisphere before they appeared on the ends of the cylinder, the axial stress had to be reduced by 50 percent to the same axial stress level as at the end of the cylinders. The simplest solution to this problem was to fabricate the hemispheres to the same thickness as the adjoining cylinder. However, this doubled the weight of the hemisphere unnecessarily.

A more elegant solution was to modify the configuration of the hemisphere by transitioning the spherical shell at the equator into a cylindrical ring whose thickness matches that of the adjoining cylinder (Figure3). The cyclic fatigue life of 12 in OD hemisphere with cylindrical skirt when tested under external pressure was found to be an order of magnitude longer than of the hemispheres with the same membrane design stress but without the cylindrical skirt. To reduce the membrane stress at the penetrations to the 130,000 psi membrane hoop stress level in the cylinders, the thickness of the spherical shell was either increased generally or locally around the penetration by incorporation of a boss.

The **findings** of the ceramic R & D program at NOSC (References 4-8) further expanded the structural ceramic technology pioneered by ORL ceramic housing program at Pennsylvania State University in 1961-1964 period. The major findings were:

1. **Internal reinforcement to cylinders** by insertion of metallic ring stiffeners is more cost effective than grinding deep integral ceramic ribs. The metallic ring stiffeners can be inserted into the interior, or fitted to the ends of cylinders and bonded in place, or they can be fitted into the metallic joint between the cylinders (Figures 4 and 5).
2. **Initiation of cracks can be delayed** at the ends of ceramic housings by inserting them into metallic U-shaped rings bonded to the ends of the housings with epoxy adhesive. The depth of the seat in the ring must exceed the thickness of the ceramic shell by a factor $\geq$2.5 and the layer of epoxy adhesive trapped underneath the plane bearing surface of ceramic must be $\leq$0.010 inches(Figure 6).
3. Ceramic cylinders of 96% alumina supported by metallic joint stiffeners **do not fail under a single pressurization** at nominal maximum membrane hoop stress level of $\leq$-300,000 psi, nominal maximum membrane axial bearing stress of $\leq$-150,000 psi, and maximum local radial tensile stress on the bearing surface of $\leq$+28,000 psi.
4. **Cyclical pressurization fatigue life** is primarily a function of the average compressive axial bearing stress at the housing ends encapsulated in epoxy filled titanium rings (References 14-17). When the maximum nominal membrane **hoop stress is $\leq$-133,500 psi** the nominal maximum membrane **axial bearing stress $\leq$-66,620 psi**, and the maximum local **radial stress on the bearing surface $\leq$+19,630 psi**, the cyclical life of the 96 % Al_2O_3 ceramic housing is $\geq$3000 cycles (Figure 6).

These stress levels were generated by 9000 psi (62 MPa) external pressure acting on 12.0 x 11.18 x 18 in Al_2O_3 cylinders serving as test specimens in this program. When the external pressure is increased to 12,000 psi (82.7 MPa) generating -178,000 psi and -

88,000 psi maximum nominal hoop and axial stresses, the cyclical fatigue life decreases to 1000 cycles, and at 15,000 psi (103.5 MPa) generating -225,500 psi and -111,000 psi maximum minimal hoop and axial stresses, the cyclical fatigue life decreases to 100 cycles. The cyclic fatigue life of SiC/Al_2O_3 (Reference 17) and of Zirconia toughened Al_2O_3 ceramic cylinders (Reference 15) was found to be significantly longer than of 94 and 96% Al_2O_3 at all axial bearing stress levels..

5. Penetrations can be incorporated into hemispherical end closures provided the hoop stresses around the penetration $\leq$-200,000 psi. The optimum approach is to make the thickness of the whole hemisphere equal to that of the cylinder, or to increase it locally around the penetration. For hemispheres without penetrations, the thickness can be reduced to 50 percent of cylinder thickness.

6. The axial bearing stresses at the sphere's equatorial edge can be reduced by 50% without increasing the thickness of the hemisphere by transitioning smoothly the equatorial edge of the hemisphere into a cylindrical flange whose OD and ID matches that of the adjoining cylinder, and its length extends $\geq$2.7 times its thickness at the edge.

7. Ultrasonic inspection of the ceramic cylinders and hemispheres while immersed in water was found to be reliable economical quality inspection procedure. Utilizing C-scan technique, the presence of inclusions $\leq$0.030 in in size was readily detected in the shells of the cylinders and hemispheres.

8. The cyclic fatigue life of the ceramic bearing surfaces in contact with titanium end rings (Figure 6) is maximized by polishing them to 2 rms finish, and placing them on a 0.04 in thick gasket laminated from 8 plies of 0/90 graphite fiber tape with PEEK resin bonded with 0.01 in thick epoxy layer to the titanium ring.

Navy Ceramic Housing Program

Upon the successful conclusion of the in-house NOSC research program and publication of the test findings (References 3-16), the U.S. Navy funded NCOSC to expand the NOSC program to include development of full scale housings for a Navy AUV with 20,000 feet (6100 m) depth capability.

1. The 96% Al_2O_3 was selected as the most cost effective ceramic on the basis of material cost, structural performance and availability in large sizes.
2. Smooth bore cylinders were chosen as the structural shape with the ends encapsulated in epoxy filled titanium rings and radially supported by a titanium stiffener bonded to the ends on adjacent cylinders joining them together.
3. Ceramic hemispheres with cylindrical skirts and penetrations were selected as bulkheads for the cylinders.
4. The compressive membrane stress at the penetrations was, for one type of hemispheres, kept at $\leq$200,000psi by an overall increase in wall thickness and for the other type, by varying the wall thickness from equator to pole and placing the penetrations near the equator.

One model scale and two full scale housings were fabricated from 96 % Al_2O_3 ceramic. The model scale housing was assembled from two 12 in OD x 0.434 in T x 15.375 in L cylinders joined together by a titanium joint ring stiffener bonded to edges of adjoining cylinders. The cylinder housing assembly was closed at both ends with ceramic hemispheres; one of them bare and 0.181 in thick and the other 0.271 in thick with a penetration at the apex. The maximum membrane hoop stress on the interior the cylinder was 125,000 psi, and on the interior of the hemispheres 137,000 and 117,000 psi respectively, except at the penetration where it was 163,000 psi. It successfully withstood 500 pressure cycles to 9000 psi with only minor cracks on the bearing surfaces of the edges on the cylinder and skirted hemispheres (Reference 8).

The smaller of the two full scale housings was assembled from two 25 in OD x 0.90 in T x 31.90 in L cylinders closed by ceramic hemispheres with cylindrical edge configuration; the 0.375 in thick hemisphere was without penetrations, and the 0.563 in thick hemisphere had multiple penetrations. The two 0.9 in thick cylinders were joined by a joint ring stiffener bonded to the edges of adjoining cylinders (Figure 5).

The larger of the two full scale housings was assembled from two 32 in OD x 1.15 in T x 39.53 in L cylinders closed by hemispheres whose thickness varied from 0.72 near the equator to 0.48 in at the apex equipped with cylindrical edge configurations whose length was 2.7t.. The two cylinders were joined by a joint ring stiffener bonded to the edges of adjoining cylinders. The membrane stresses on the interior of the cylinders at 9,000 psi pressure were 131,000 psi, 156,000 psi on interior of 0.375 in thick hemisphere and 204,500 psi near the penetration on the interior of the 0.563 in hemisphere. The length of the cylindrical skirt for both hemispheres was 2.7t, t denoting the cylinder thickness Reference 9).

Both housings were proof tested to 10,000 psi external pressure. The program was terminated upon successful proof testing of the large diameter housings.

The major findings of the program on fabrication of large ceramic pressure housing were:

1. Isostatically pressed and subsequently fired 96% Al_2O_3 ceramic is suitable for economic fabrication of cylindrical and spherical pressure housings with $\leq$32 in OD for 20,000 feet depth service.
2. Cylindrically shaped skirts on 12, 25 and 32 in diameter hemispheres lower the axial bearing stress on the equatorial joint to the stress level on the end of the cylinders.
3. Titanium stiffeners bonded to the edges of adjoining cylinders serve as a joint and provide the required elastic stability at a significant weight saving.
4. Large ceramic pressure housings for 20,000 feet depth are achievable with w/D ratios 0.595 for the 25 in OD housing and 0.545 for the 32 in housing.

Woods Hole Oceanographic Institute Ceramic Housings Program

When WHOI initiated a NSF funded program in 2004 for construction of an ROV/AUV for exploration of 36,000 feet (11,000 m) deep trench in the Pacific Ocean, it immediately became apparent that the pressure housing could not be fabricated from titanium, the conventional structural material used for fabrication of pressure housings, if the housings were to provide any lift for their payload (Figure 1). Among other available structural materials with high compressive strength, only ceramics had a past history for such application. With Dr. Stachiw serving as the technical consultant to the program, a project was initiated to develop ceramic housings for the WHOI vehicles.

As construction material served 96 % Al_2O_3 isostatically pressed ceramic powder; housing configuration was smooth bored cylinders; firing and subsequent grinding was the fabrication process; ultrasonic inspection and dye penetrant served as NDE techniques. The assembly of housing consisted of encapsulating the ends of ceramic cylinders and hemispheres in epoxy filled titanium joining rings, joining by clamping of joint rings on adjacent cylinders, or cylinder and titanium hemisphere. In some of the housing assemblies, two ceramic cylinders were joined by titanium couplings bonded to the ends of the cylinders. Hydrostatic proof testing to 18,000 psi served as validation of design and fabrication procedures.

There were two major departures in design criteria of WHOI housings from that of NOSC housing for the Navy. **The first design departure** was the increase in design stress. Since the NOSC housings were to be incorporated into ROV's or AUV's for use in the field by the Navy, the cyclic fatigue life of ceramic bearing surfaces at the joints had to exceed 10 years during which 500 deployments to design depth of 20,000 feet were projected. To achieve this reliably the maximum nominal membrane hoop stress could not exceed -150,000 and maximum nominal membrane axial stress -75,000 psi. The 100 percent safety margin based on -300,000 psi minimum compressive strength was considered more than adequate to achieve the desired cyclic fatigue life.

This was not the case with ceramic housings for 36,000 foot depth service by WHOI. A 100% safety margin (i.e. 150,000 psi design stress) would result in very heavy housings providing unacceptably low payload capability. The only way for raising the buoyancy of the housings was to reduce the safety margin from 100 to 50 percent (i.e. increase the maximum nominal hoop design stress from 150,000 psi to 200,000 psi). Because of the higher design stress, the cyclic fatigue life projected for WHOI housings is projected to decrease from 1000 to only 100 pressure cycles. This is not a serious drawback as the cyclic service life of the WHOI vehicle is projected to be less than 100 dives to 36,000 feet design depth over a period of 10 years. If the total of dives to 36,000 ft design depth is less than 10 as it is projected to be, and the remainder of the dives is to $\leq$20,000 ft, then the cyclic fatigue life is projected to be in excess of 1000 dives.

The second major departure is the **elimination** of separate ceramic hemispheres that had to be configured with a cylindrical skirt to reduce the axial bearing stress at the joint with the cylinder. By combining the hemisphere with the cylinder into a single unit, the requirement for a joint with a limited fatigue life between the cylinder and the hemisphere was eliminated with associated significant weight saving. Instead of two ceramic or titanium hemispheres in each housing, a single titanium hemisphere with multiple penetrations was chosen for access to the interior of the housing.

The shapes selected for fabrication from isostatically pressed 96% Al_2O_3 were 14 in and 7.5 in OD cylinders, some open at both ends, and some capped on one end. The typical dimensions were 14.0 in OD x 12.8 ID x 17 in L, and 7.5 in OD x 6.72 in ID x 17 in L.

All of these shapes were fabricated and dye penetrant inspected for exterior cracks at COORSTEK, Golden CO. Subsequently they were ultrasonically C-scanned for voids and cracks in the body of the shell at STORK Materials Testing and Inspection, Ranch Dominguez, CA. No cracks or internal voids $\geq$0.031 in (0.8mm) were detected during the inspections, indicating high quality castings.

The ends of the cylinders were inserted into epoxy filled titanium circular U shaped rings with seat depth equal to 3 times the shell thickness. Prior to insertion of the ceramic shell into the epoxy filled end ring, a 0.005 in Kapton® polyimide film was inserted into the epoxy filled end ring and pushed downward until it rested on top of the plane titanium surface. The configuration of the end rings was patterned after the experimentally validated end rings developed by Dr. Stachiw at NOSC during the Navy's ceramic housing development program in 1984.

Both the 7.5 in and 14.0 in OD cylinders were capped by titanium hemispheres. Prior to being accepted for service the ceramic cylinders were assembled into housings and proof tested twice to 18,000 psi external pressure while the acoustic emissions were recorded. Following the proof test, two housing assemblies were pressure cycled 10 times to 16,500 psi, followed by a long-term pressurization to 16,500 psi. Acoustic emissions were monitored during all the pressure testing. Only if the acoustic emissions decreased significantly during the second pressurization was the cylinder considered fit for incorporation into the vehicle.

Major findings of the program on fabrication of ceramic housings for WHOI are:

1. 96% Al_2O_3 ceramic is suitable for economic fabrication of cylindrical and spherical pressure housings with $\leq$14 in OD for 36,500 feet depth.
2. For service life requiring $\leq$100 dives to design depth, the housings can be designed for <u>201,000</u> peak hoop membrane and <u>100,000 psi</u> axial bearing stress.

3. Cylinders with integral caps save weight and fabrication cost by eliminating one set of joints in a housing.

Each of the 14 in OD ceramic housing assembled from a capped cylinder mated to an open cylinder closed on the other end with a titanium hemisphere will provide over 50 lbs of buoyancy for the WHOI vehicle. Still this is not sufficient for the payload of a vehicle for a projected 100 hour mission to the deepest spot in the ocean. The difference is made up by incorporating 1700 ceramic 3.5 in OD ceramic buoys into the vehicle framework, each providing approximately 0.5 lbs of lift. These ceramic buoys were specifically developed by DeepSea Power and Light Co, San Diego, CA for the WHOI vehicle. Of seamless construction, spin cast in 99.9 % Al_2O_3, they are proof tested twice by DSPL to 30,000 psi prior to delivery to preclude any possibility of implosion in service at 16,500 psi design depth (Reference19). Ten inch diameter ceramic buoys were also developed for this application but not utilized because of qusality control shortcomings during fabrication of pre-production units (Reference 17). Together with the four ceramic cylindrical housings they provide over 1000 lbs of buoyancy for the payload of the deep diving vehicle.

The interesting characteristic of the ceramic housings and floats is that their buoyancy increases with depth (approximately 7 % at 36,000 ft) generating over 100 lbs of additional buoyancy, making them the ideal choice for housings and buoys slated for submersion to abyssal depths.

REFERENCES*

1. "Hulls for Deep Submergence Capsules," J.D. Stachiw, American Ceramic Society Bulletin Vol. 47, No. 2, February 1968.
2. Pressure Resistant Ceramic Housings for Deep Submergence Unmanned Vehicles," Marine Technology Society Journal Vol. 24, No. 2, June 1990.
3. "Exploratory Evaluation of Beryllia Ceramic Cylindrical Housing for Deep Submergence Service," NOSC Technical Report #951, J.D. Stachiw, Naval Ocean Systems Center, January 1984.
4. "Exploratory Evaluation of Alumina Ceramic Cylindrical Housings for Deep Submergence Service: The Second Generation NOSC Ceramic Housings," NOSC Technical Report #1176, J.D. Stachiw, J.L. Held, Naval Ocean Systems Center, September 1987.
5. "Exploratory Evaluation of Alumina Ceramic Cylindrical Housings for Deep Submergence Service: Third Generation Housings: Volumes I and II, NCCOSC Technical Report #1314, J.D. Stachiw, Naval Command, Control and Ocean Surveillance Center, June 1993.
6. "Exploratory Evaluation of Alumina Ceramic Cylindrical Housings for Deep Submergence Service: Fourth Generation Housings," NOSC Technical Report #1355, J.D. Stachiw, Naval Ocean Systems Center, June 1990.
7. "Adhesive Bonded Joint with Improved Cyclic Fatigue Life for Alumina Ceramic Cylinders and Hemispheres: Fourth Generation Housings," NCCOSC Technical Report#1587, J.D. Stachiw, Naval Command, Control and Ocean Surveillance Center, August 1993.
8. Evaluation of Scale Model Ceramic Pressure Housings for Deep Submergence Service: Fifth Generation Housings," NCCOSC Technical Report #1582, J.D. Stachiw, R.P Johnson and R .R. Kurkchubasche, Naval Command, Control and Ocean Surveillance Center, March 1993.
9. "Design and Structural Analysis of Alumina Ceramic Housings for Deep Submergence Service," NCCOSC Technical Report #1583, R.P. Johnson, J.D. Stachiw and R.R. Kurkchubasche, Naval Command, Control and Ocean Surveillance Center, March 1993.
10. "Exploratory Study of Joint Rings for Ceramic Underwater Pressure Housings," NCCOSC Technical Report #1586, J.D. Stachiw, R.P. Johnson and K.K. Kurkchubasche, Naval Command, Control and Ocean Surveillance Center, May 1993.
11. "Effect of Different Axial Bearing Supports on the Fatigue Life of Ceramic Pressure Housings," NCCOSC Technical Report #1607, J.D. Stachiw, R.P. Johnson, R.R. Kurkchubasche, Naval Command , Control and Ocean Surveillance Center, October 1993.
12. "Structural Performance of Cylindrical Pressure Housings of Different Ceramic Compositions under External Pressure Loading; Part 1—Isostatically Pressed Alumina Ceramic, NCCOSC Technical Report #1590, J.D. Stachiw, R.P. Johnson and R.R. Kurkchubasche, Naval Command, Control and Ocean Surveillance Center, August 1993.
13. "Structural Performance of Cylindrical Pressure Housings of Different Ceramic Compositions under External Pressure Loading; part II—Zirconia Toughened Alumina Ceramic," NCCOSC Technical Report #1593, J.D. Stachiw, R.P. Johnson and R.R. Kurkchubasche, Naval Command, Control and Ocean Surveillance Center, December 1993.
14. "Structural Performance of Cylindrical Pressure Housings of Different Ceramic Compositions under External Pressure Loading; Part III—Sintered Reaction Bonded Silicon Nitride Ceramic," NCCOSC Technical Report #1592, J.D. Stachiw, R.P. Johnson and R.R. Kurkchubasche, Naval Command, Control and Ocean Surveillance Center, June 1994.
15. "Structural Performance of Cylindrical Pressure Housings of Different Ceramic Compositions under External Pressure loading; Part V—Silicon Carbide Particulate Reinforced Alumina Ceramic," NCCOSC Technical Report 1594, J.D. Stachiw, R.P. Johnson and R.R. Kurkchubasche, Naval Command, Control and Ocean Surveillance Center, December 1993.
16. Evaluation of Non Destructive Inspection Techniques for Quality Control of Alumina Ceramic Housing Components," NCCOSC Technical report #1588, R.R. Kurkchubasche, R.P. Johnson and J.D. Stachiw, Naval Command, Control and Ocean Surveillance Center, September 1993.
17. "Alumina Ceramic 10 in Flotation Spheres for Deep Submergence ROV/AUV Systems," J.D. Stachiw and Donald Peters, MTS/IEEE Oceans 2005 Conference, Washing, D.C., September 18-23, 2005.
18. "Alumina Ceramic 3.6 in Flotation Spheres for 11 km ROV/AUV Systems," Steve Weston, J.D. Stachiw, Ray Merewether, Mark Olsson and George Jemmott, MTS/IEEE Oceans 2005 Conference, Washington, D.C., September 18-23, 2005.

*All references can be purchased at www.hydroports.com

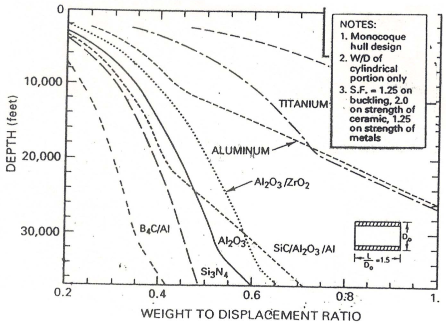

Figure 1 Weight to Displacement Of Cylinders

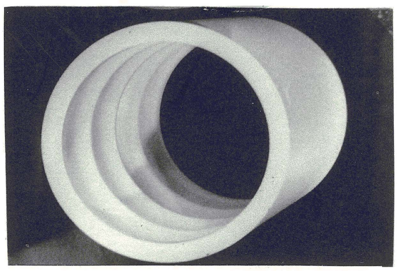

Figure 2 Ceramic Cylinder with Integral Stiffeners

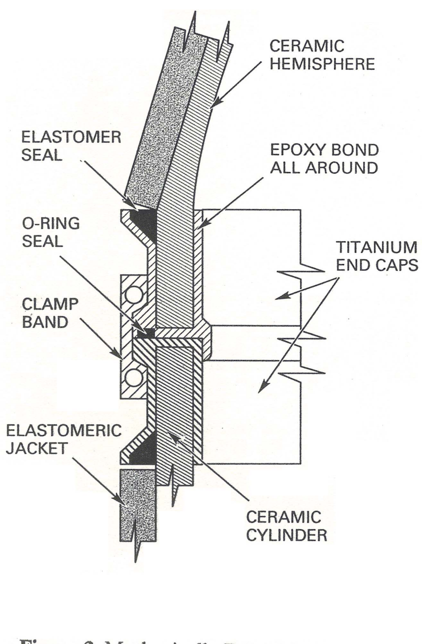

Figure 3 Mechanically Fastened Joint For Hemispheres

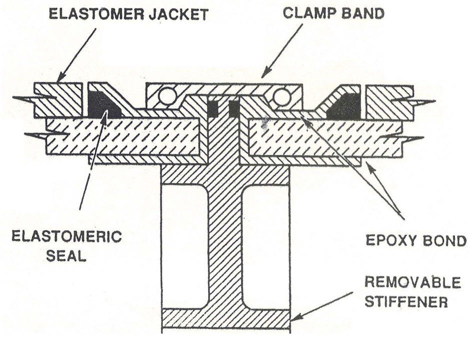

Figure 4 Mechanically Fastened Joint With Removable Stiffener For Cylinders

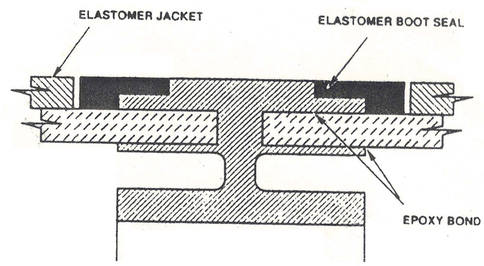

Figure 5 Bonded in joint with Integral Stiffener

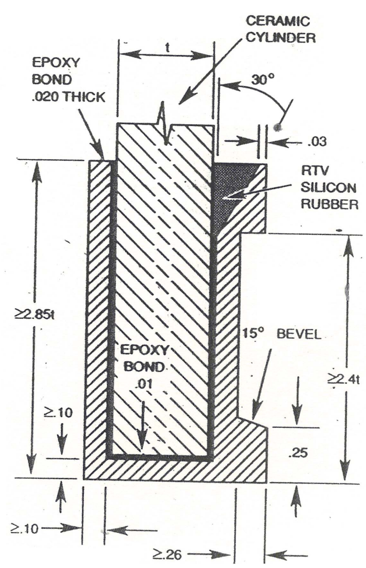

Figure 6 Typical bonded End Cap for Cylinders and Hemispheres

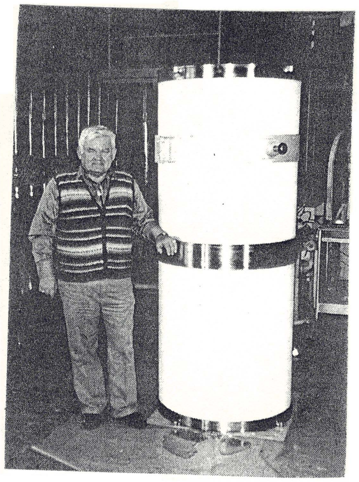

Figure 8 32 in OD X 80 in L ceramic housing for 20,000 ft depth service

Figure 7 25 in OD X 64 in L ceramic housing for 20,000 ft depth service

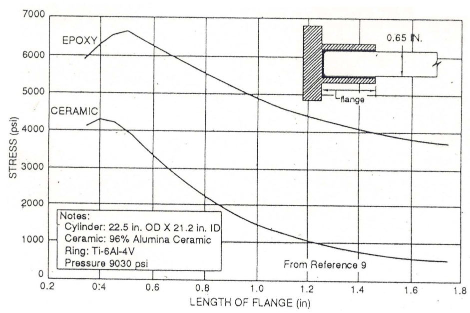

Figure 9 Effect of flange length on principal stress on the bearing surface

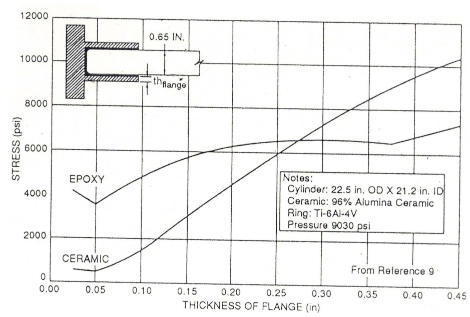

Figure 10 Effect of flange thickness on principal stress on the bearing surface

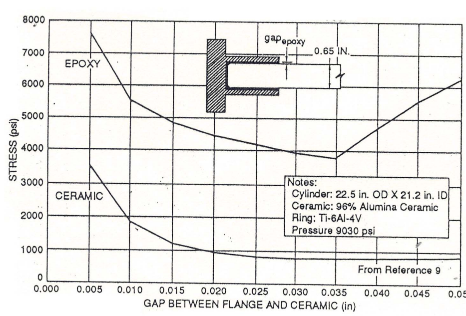

Figure 11 Effect of radial gap on principal stress on the bearing surface

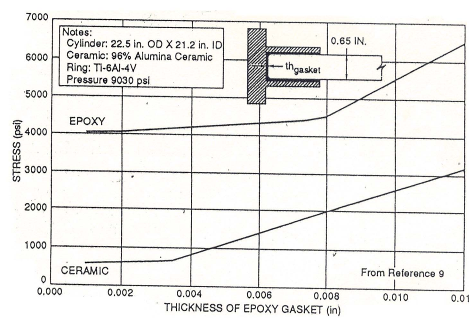

Figure 12 Effect of gasket thickness on principal stress on the bearing surface